**REPAIR, EVALUATION, MAINTENANCE, AND
REHABILITATION RESEARCH PROGRAM**
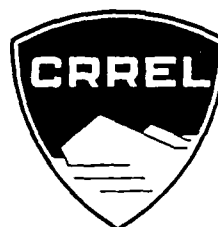
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TECHNICAL REPORT REMR-CS-26

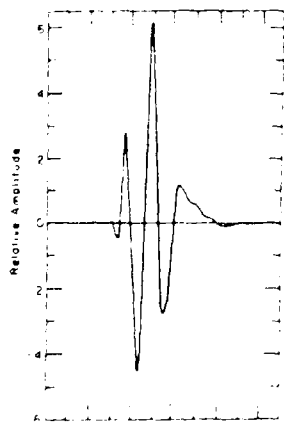# ANALYSIS OF A SHORT PULSE RADAR SURVEY OF REVETMENTS ALONG THE MISSISSIPPI RIVER

by

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CS	Concrete and Steel Structures		EM	Electrical and Mechanical	
GT	Geotechnical		EI	Environmental Impacts	
HY	Hydraulics		OM	Operations Management	
CO	Coastal				

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COVER PHOTOS

TOP   Transmit-receive (bistatic) antenna configuration.

MIDDLE   Transmitter-receiver in water.

BOTTOM   Typical pulse radar transmitted wavelet.

Unclassified

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FIELD	GROUP	SUB-GROUP	Radar Revetments	Short pulse radar survey Underwater survey techniques

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

A short pulse radar survey was conducted in McKellar Lake directly across from the
US Army Corps of Engineers dock facility at Ensley Engineer Yard. The intent was to examine
radar responses to revetments placed on the bottom of the lake to retard erosion and to
determine if such responses could be interpreted as indicative of erosion within the revet-
ments themselves. A radar transmitting a pulse with a center frequency of about 60 MHz was
towed on the water surface both alongshore and on/off shore. The results show excellent bot-
tom profiling to about the 25-ft depth that apparently conforms to general performance
expectations of this system. Severe direct coupling between transmit and receive antennas
masked responses from depths of 11 ft or less. Several diffraction hyperbolae distinctly
originating from the bottom may have been caused by discontinuities in the revetments.
Unfortunately, no ground truth investigations were carried out by the survey party to ascer-
tain the exact cause, and no maps showing the exact location of the survey are available.
Several recommendations are made to improve the quality of data from future surveys.

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Preface

The study reported herein was authorized by Headquarters, US Army Corps of Engineers (HQUSACE), under Civil Works Research Work Unit 32270, "Underwater Survey Techniques." The study was conducted as a part of the Concrete and Steel Structures Problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. The REMR Overview Committee consists of Mr. James E. Crews and Dr. Tony C. Liu, HQUSACE. The Technical Monitor was Dr. Liu.

This report was prepared by Dr. Steven A. Arcone, Snow and Ice Branch, US Army Cold Regions Research and Engineering Laboratory (CRREL), and is based on a radar survey conducted by Mr. Arnold Dean, Ice Engineering Research Branch, CRREL. The work was monitored at the US Army Engineer Waterways Experiment Station (WES) by Mr. Henry T. Thornton, Jr., Concrete Technology Division (CTD), Structures Laboratory (SL), under the supervision of Messrs. Bryant Mather, Chief, SL, and Kenneth L. Saucier, Acting Chief, CTD. Mr. William McCleese, CTD, was REMR Program Manager. This report was edited for publication by Mrs. Gilda Miller, Information Products Division, Information Technology Laboratory, WES.

Commander and Director of CRREL during publication of this report was COL Morton C. Roth, CE. Technical Director was Dr. Lewis E. Link, Jr.

Commander and Director of WES is COL Larry B. Fulton, EN. Technical Director is Dr. Robert W. Whalin.

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Contents

Conversion Factors, Non-SI to SI (Metric)
Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
inches	25.4	millimetres

ANALYSIS OF A SHORT PULSE RADAR SURVEY OF REVETMENTS
ALONG THE MISSISSIPPI RIVER

Introduction

1. In August 1985, the US Army Cold Regions Research and Engineering Laboratory (USACRREL) conducted a limited radar survey above a revetment mat in McKellar Lake, directly across from the dock facility, US Army Engineer District (USAED), Memphis, at Ensley Engineer Yard on the Mississippi River near Memphis, TN. The intent was to determine if the radar had sufficient resolution to detect erosion in or under the mat, thereby proving it as an efficient diagnostic maintenance tool. The radar employed has been commercially available since approximately 1971 and is designed for land subsurface exploration in generally dry conditions. Therefore, the system itself had certain operational difficulties with the antennas floating on the water surface. However, in spite of this, enough information was gathered to assess the radar's ability to perform this task.

2. The surveys were conducted by Mr. Arnold Dean of USACRREL who operated the equipment and gathered the data but was on temporary leave from USACRREL at the time of preparing the results into report form. USACRREL has some of Mr. Dean's original data logs, but they have not answered all of the author's questions while preparing this report. Consequently, there may be some inaccuracies in reconstructing the facts of this survey such as in assessing the length of the profiles or the time scale in the records. There will also be a distinct lack of personal observations for the radar profiles, such as when the system lost power or waves rocked the antennas, to explain artifacts in the data. Observations noted in the report are speculation of the author unless noted otherwise. Generally however, such details will be of less significance than the results of the radar survey itself.

3. Of major interest to the USAED, Memphis, and to the US Army Engineer Waterways Experiment Station (WES), for whom this work was performed, is a description of the equipment and its general operation so that an initial assessment may be made of its use for other possible projects. Consequently, an extensive description is included in this report. This is followed by a description of the revetments with emphasis on their features from an electromagnetic wave propagation point of view. The Results and Discussion,

paragraphs 20 through 27, concentrate on a qualitative description of the many interesting phenomena present. The conclusions and recommendations in paragraphs 28 and 29 summarize the results and make recommendations for improving the operation.

Subsurface Radar

4. A commercially available subsurface radar system (also known as an impulse, short pulse, or ground penetrating radar system) consists of a control unit, antennas and cables, magnetic tape recording device, and a power supply. The control unit generates timing signals to key the transmitter on and off and synchronize this keying with the receiver. It controls the scan rate (how fast individual echo scans are compiled), the time range over which one wants to view the echoes, and the gain to be applied to the echoes. The antennas are usually separated (transmit and receive) and are designed to radiate a very short pulse of only nanoseconds in duration. Consequently, they are confined to very low-gain, nondirective radiation patterns. Electronics for the transmitter and receiver are usually incorporated into the antenna unit. Data are usually stored on magnetic tape, therefore requiring that the very high-frequency radiated signals be converted into an audio frequency facsimile before storage. This conversion is done by a sampler incorporated into the receiver. Data are generally played back in strip chart form whereby signal intensity is displayed as darkness, just as with commonly used hydrographic depth sounders employed with sonar.

Control unit

5. The radar system was controlled by a GSSI (Geophysical Survey Systems, Inc., Hudson, NH) SIR Model 4000 mainframe that triggers pulses at a repetition frequency of approximately 50 kHz and compiles the received pulses into 25.6 scans per second (higher or lower rates are possible). A variety of linear time range gain rates may be applied to the scans to suppress the higher amplitude early returns (especially the direct coupling between transmit and receive antennas) and enhance the lower amplitude later returns. An overall system gain was also utilized. Power was supplied from the boat that towed the antennas.

6. Each scan of return events (echoes) can be viewed at a variety of time ranges internally calibrated by the system using an oscillator at fixed

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frequency. The graphic records will show these time calibrations translated into water depth, d , by using the simple formula

$$d = \frac{ct}{2n}$$

where

   t = time in nanoseconds

   c = velocity of wave propagation in air (30 cm/ns or 1 ft/ns)*

   n = the index of refraction for water

At room temperature, $n = 9$. Further discussion of wave propagation in water is given in paragraph 8. The factor of 2 in the equation accounts for the round trip, the outgoing signal plus the return echo.

Antennas

7. The antennas used for the survey are of prototype design developed by GSSI in the late 1970's and are currently referred to as Model 3207. Their design is characterized by a variety of names (biconical, batwing, bowtie), but they are mainly flared dipoles with resistive coating. This coating accounts for the fact that when excited by a short pulse the antennas will not resonate and, therefore, will radiate the shortest pulse possible. The antennas are the distinct feature of subsurface radar and warrant further discussion.

8. A schematic of the antenna design is shown in Figure 1, and a typical radiated wavelet is shown in Figure 2 (not from the antenna in Figure 1, but from similar designs). The wavelet consists of a very few oscillations that quickly attenuate, as opposed to conventional surveillance radar that produces bursts of a carrier frequency lasting for hundreds of oscillations. The time units of the wavelet are arbitrary but range from 1 to 10 nanoseconds. The short-burst nature of this wavelet gives it a very broad bandwidth. Antennas of this design are mainly characterized by the center frequency of their spectrum, or roughly, the frequency at which the peak of the power spectrum lies. This is found with good accuracy by simply inverting the period of the major oscillation. The author's personal experience with model 3207 is that in air the peak lies at approximately 280 MHz. When placed on ground

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* A table of factors for converting non-SI units of measurement to SI
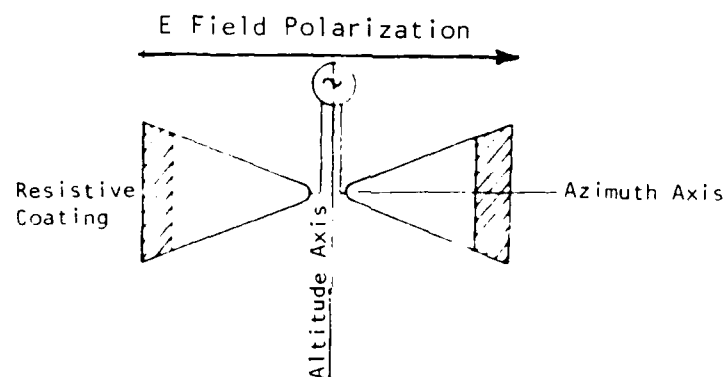 (metric) units is presented on page 3.

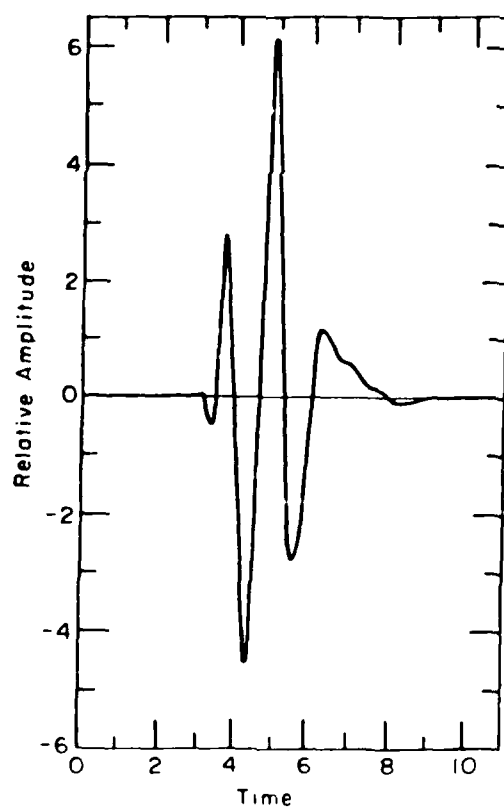Figure 1.   Schematic of a short pulse radar antenna

Figure 2.   A typical transmitted wavelet

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where n = 2 this lowers to about 150 MHz due to impedance loading. As will be seen in the raft setup on the water, the center frequency dropped well below 100 MHz.

9. Separate transmit and receive antennas are generally used because echoes can return from near-surface targets before the transmit antenna has stopped radiating. A photograph of the antenna configuration used in this survey is shown in Figure 3. Each antenna was placed in a small, recreational raft, and the separate units were braced together. The separation of the antennas is estimated at about 1.5 to 2.0 m. This separation will be seen later to cause severe reverberation problems between the antennas. The bracing of the two units have also caused reverberation if the system periodically lost water contact in the presence of waves or during the boat's acceleration. The antennas were polarized perpendicular to the direction of tow (or profiling), a fact that could have some consequence in light of arguments for or against transmission through the revetments.

10. An important quantity that has never been experimentally investigated is the directionality of the radiation into a dielectric medium. Theoretical studies have shown that very small dipole antennas, operating at a fixed frequency and polarized parallel to the ground or water as in this case, radiate a complicated pattern in the azimuthal plane (Figure 1; the azimuthal plane is perpendicular to the long axis of the antenna) beneath the antenna. The strongest radiation occurs to either side at an angle from vertical of $\sin^{-1}$ (1/n), and for our water case the angle would be only 6 deg. This pattern becomes more lobed in the altitude plane (the plane containing the long axis of the antenna). For more extensive discussion, the reader is referred to Engheta, Papas, and Elachi (1982).* It is viable to say that the directivity in water is theorized to be somewhat more directive than if the dipole were in air, with the strongest intensity directed along a cone at 6 deg from vertical.

Graphic display

11. All data presented were recorded in an analog mode, and the scans are displayed consecutively on resistively treated chart paper by electrostatic burning so that darkness is proportional to signal amplitude. The

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* N. Engheta, C. Papas, and C. Elachi. 1982 (Nov-Dec). "Radiation Patterns of Interfacial Dipole Antennas," Radio Science, Vol 17, No. 6, pp 1557-1566.

a. Photograph of revetment
along the shore
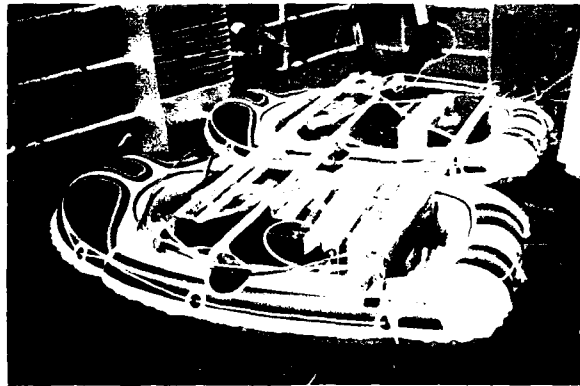
b. Transmit-receive (bistatic)
antenna configuration

c. Position in the water

Figure 3. Three views of bistatic
antenna configuration

translation of a series of scans of hypothetical, identical events into the graphic representation is shown in Figure 4. This is a superior mode of display when signal returns are strong as the continuity of events or banding from a single reflector is easy to recognize. The identification of these bands indicates coherency (i.e. retention of the phase integrity of the incident wavelet) in the reflected wavelet.
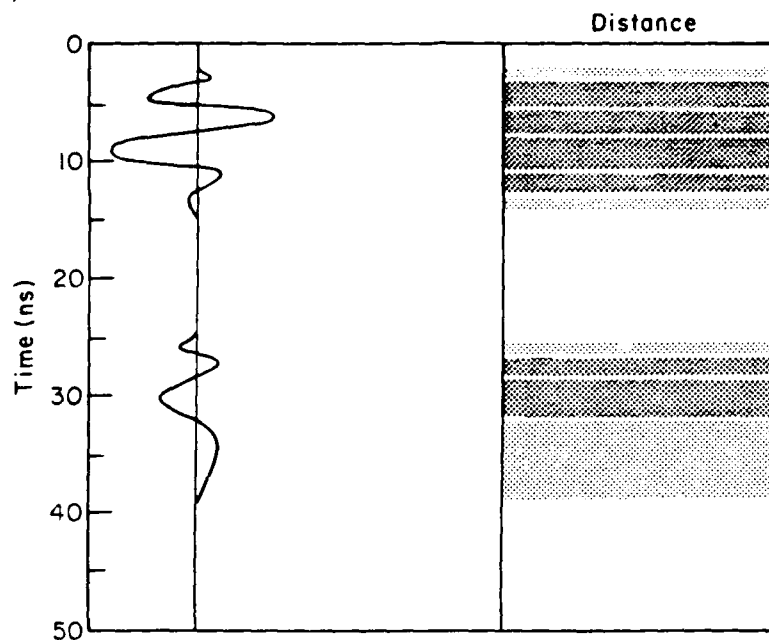

Figure 4. Hypothetical scan consisting of two events and its equivalent graphic representation should these wavelets remain unchanged as the antennas move a short distance. Thin white lines in the graphic indicate zero amplitude; their continuity in a record indicates coherency in the radar returns

Propagation

12. A schematic representation of the wave propagation events that occur in the surveying described here is given in Figure 5. The events are depicted by arrows as if they were solitary rays, but in fact they are complex electromagnetic fields expanding in three dimensions. The idealized wavelet of Figure 2 forms by about 1 to 2 m beneath the transmit antenna.

13. The two events labeled direct coupling in Figure 5 are transmissions passing directly from transmit to receive antenna, one in air and one in water. These are known as near-field events and die out very quickly with distance. Unfortunately, they are very strong in the proximity of the antennas and require antenna separations much greater than were actually employed.
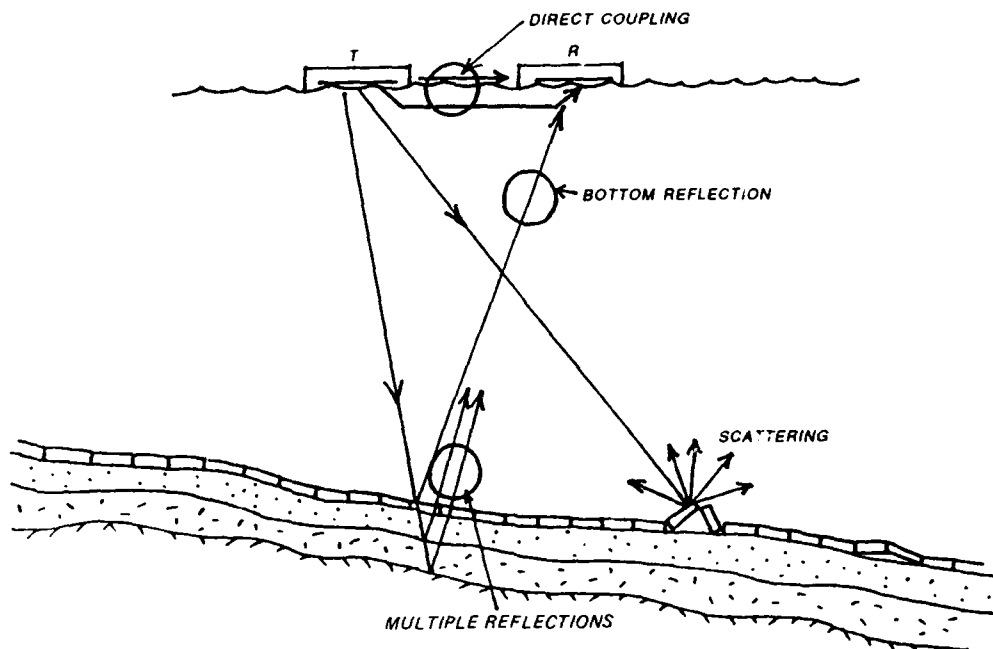
Figure 5. Schematic of some expected radar events for the
revetment survey. The event marked scattering can be a coherent
or incoherent event. Coherent examples characterized by hyper-
bolic spatial patterns (caused by changing distance between
antenna and target) will be seen in the data

These events tend to reverberate between antennas and can mask a significant
portion of the record.

14. Events such as the one labeled bottom reflection are truly reflec-
tions only if the bottom is flat over a distance of several wavelengths.
Otherwise, the echoes are really scatter and are often incoherent and appear
as noise. Coherent noise is reflections from objects not of interest. The
dominant wavelength L of the transmitted pulse in water is found from the
formula

$$L = \frac{c}{nf}$$

where c and n are as previously defined, and f is the center frequency
of the pulse spectrum. At f = 100 MHZ , L = 33 cm , and at f = 50 MHz ,
L = 66 cm . Therefore, a small flat surface area of only a few square metres
is required to produce a coherent reflection. However, one will not be able
to accurately locate the direction of a reflection due to the large beamwidth

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of the antennas. If the river bottom is flat, then the direction of the reflection is directly beneath the boat.

15. Also shown in Figure 5 are events called multiple reflections that are reverberations within the stratification of the bottom sediments, including revetments. Such events are generally much weaker than the primary bottom reflection because of the large electromagnetic wave impedance contrast between the water and bottom (not true for saturated fine-grain bottom sediments). The reflection coefficient for a water/concrete revetment interface is estimated to be 0.64. The actual value may be near -1.0 due to the wire grid holding the concrete blocks together. An absolute value of unity indicates total reflection. When penetration of the bottom does occur, the subsurface reflections often appear in many multiples. Resolution of layers closer than L is generally not possible.

16. A severe limitation to the use of subsurface radar is signal attenuation. This occurs primarily due to antenna-ground impedance mismatch, the geometric spreading of the beam, wave attenuation due to the conductivity of the water (conversion of wave energy into electric current energy), and losses due to transmission through the bottom sediments. Generally, GSSI radars can tolerate up to a 120-dB loss in transmitted signal amplitude. Mismatch losses are difficult to estimate, but the other factors are not. Figure 6 graphs the losses expected as a function of water depth for geometric spreading and conductive absorption at 50 and 100 MHz for a water conductivity of 0.02 S/m (Siemens/meter or mhos/m). The loss values account for the round trip of propagation. Assuming antenna gain and mismatch losses to be about 10 dB, we see that maximum expected penetration of a 100-MHz wavelet is about 10 m and slightly more at 50 MHz. Higher values of conductivity will further decrease penetration.

17. An additional problem associated with transmission in a conductive medium is wavelet distortion. Generally, higher frequencies in the pulse spectrum suffer far more attenuation than do lower frequencies; thus causing the pulse to spread out. Figure 7 shows that this is not to be expected for the Mississippi River. After 10 m (5-m depth) of propagation of a 100-MHz wavelet, there is hardly any change in wave shape despite great attenuation. Lower frequency wavelets will also remain free of distortion.
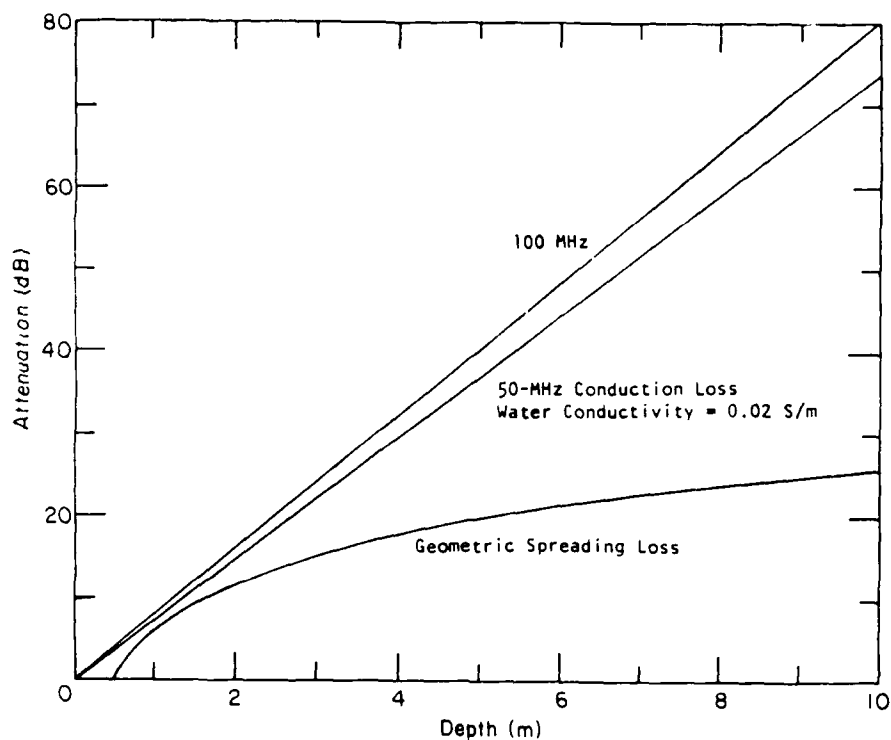
Figure 6. Attenuation due to conductive loss and geometric spreading of 50- and 100-MHz signals propagating in 0.02-S/m conductivity material
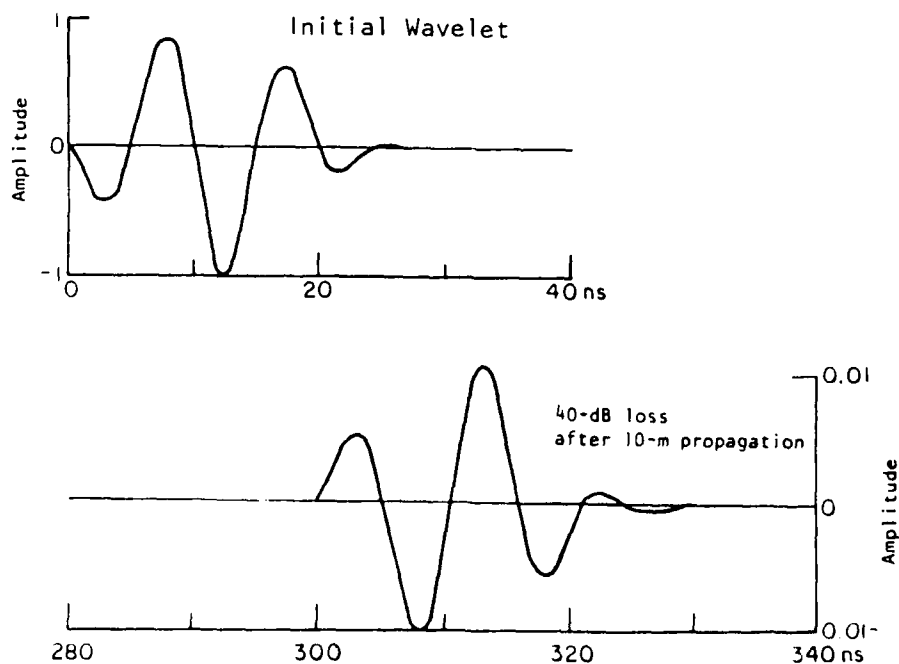

Figure 7. The 100-MHz wavelet is seen to undergo insignificant distortion but substantial attenuation after 10-m propagation (5-m depth), including a phase reversal off an assumed wire grid

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Revetments

18. A schematic diagram of the revetment map is shown in Figure 8. The mat consists of concrete blocks, approximately 17 by 48 by 3 in. in dimension, wired together into long articulated mats that are laid down side by side. Interblock wiring is fixed to wires that are cast into the blocks. The resulting grid size of the wire mesh is approximately 15 by 32 in. or about 38 by 81 cm. This metallic grid is extremely important in arguments pertaining to whether or not the radar signals can penetrate the revetments into the sediments below. Any metal grid spacing closer than L/2 will not pass electromagnetic waves with an electric field polarized parallel to the wire direction.

19. Assuming the index of refraction to be about 2.0 in the concrete (assuming the concrete is hydrologically impermeable), then L/2 at 100 MHz is equal to 75 cm, and is greater at lower frequencies. Consequently, radiation at any frequency less than 100 MHz for both profile directions indicated in Figure 8 should not penetrate the revetments.

Results and Discussion

20. Figures 9 and 10 display the graphic records of several profiles that were made both perpendicular and parallel to the shore near the Wolf River Channel near Memphis Harbor. The upper record of Figure 9 was made (reading left to right) with the antennas towed away from shore. The lower record contains a return to shore, a turn around, and then a profile away from the shore. The direct coupling between antennas and the bottom reflection are indicated. Arrows point to hyperbolic shapes originating at the bottom. In Figure 10 are three sections of one continuous (read left to right, and down the figure) alongshore profile. The numerous discontinuities in the horizontal direction are believed to be a malfunction of the radar system. No notes are available concerning the length of these profiles, but it estimated that each displayed section is approximately 20 to 30 m long.

21. Figure 9 shows many interesting features. The direct coupling is divided into two parts. The first two wider bands are the air path coupling, and the next series of approximately 10 dark bands are the water path coupling. This useless information extends approximately 200 ns into the record
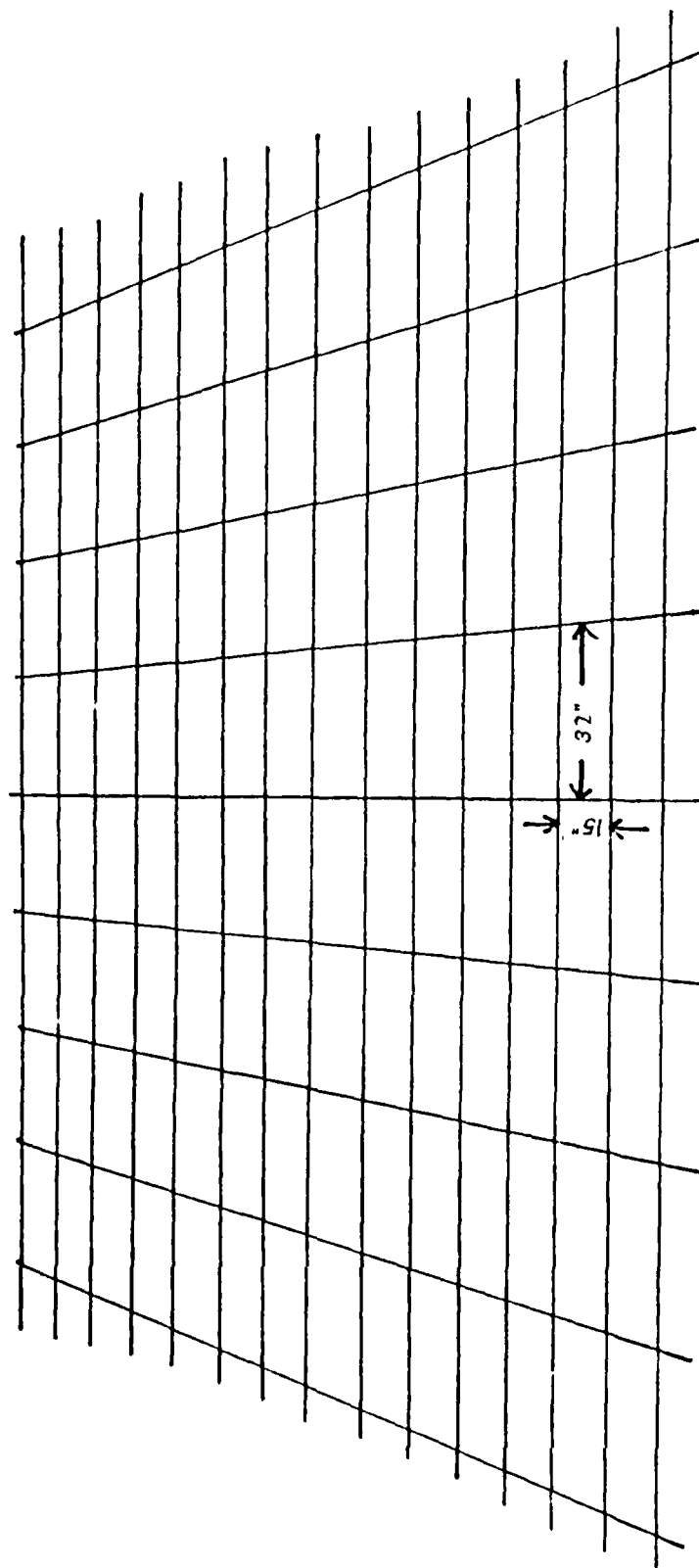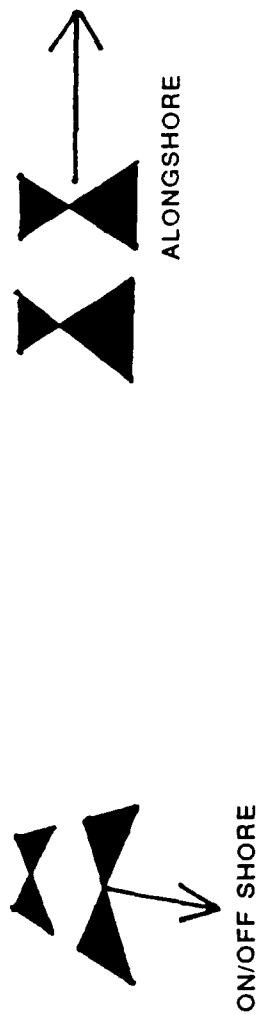
Figure 8. Orientation of the antenna polarization for the surveys relative to the wire grid of the revetment mats
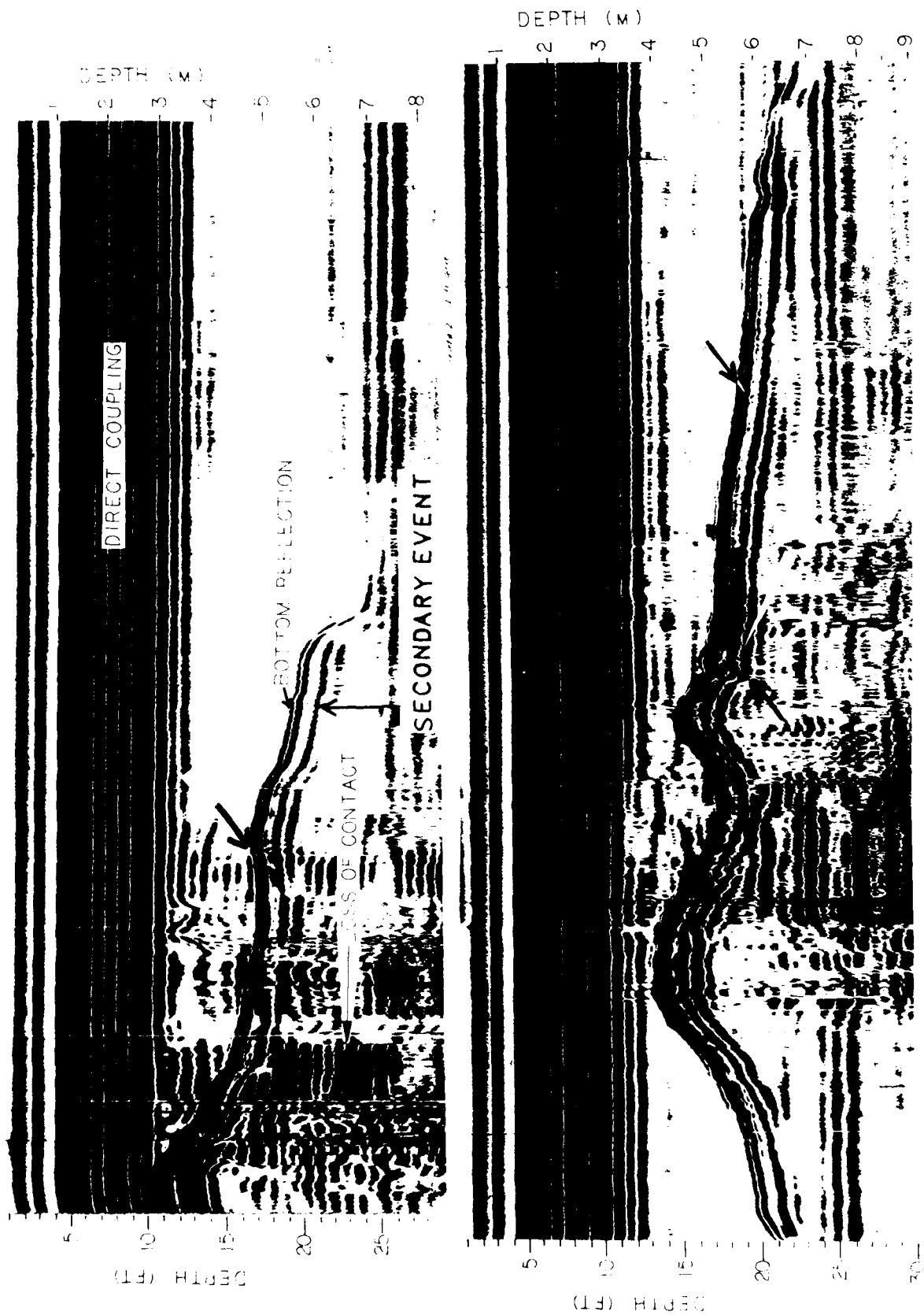
ALONGSHORE

ON/OFF SHORE

32"

15"

Figure 9. Radar profiles onshore and offshore over revetment mat. Black arrows point to hyperbolae that are indicative of local bottom disturbances. Estimated length of each section is 10 to 15 m
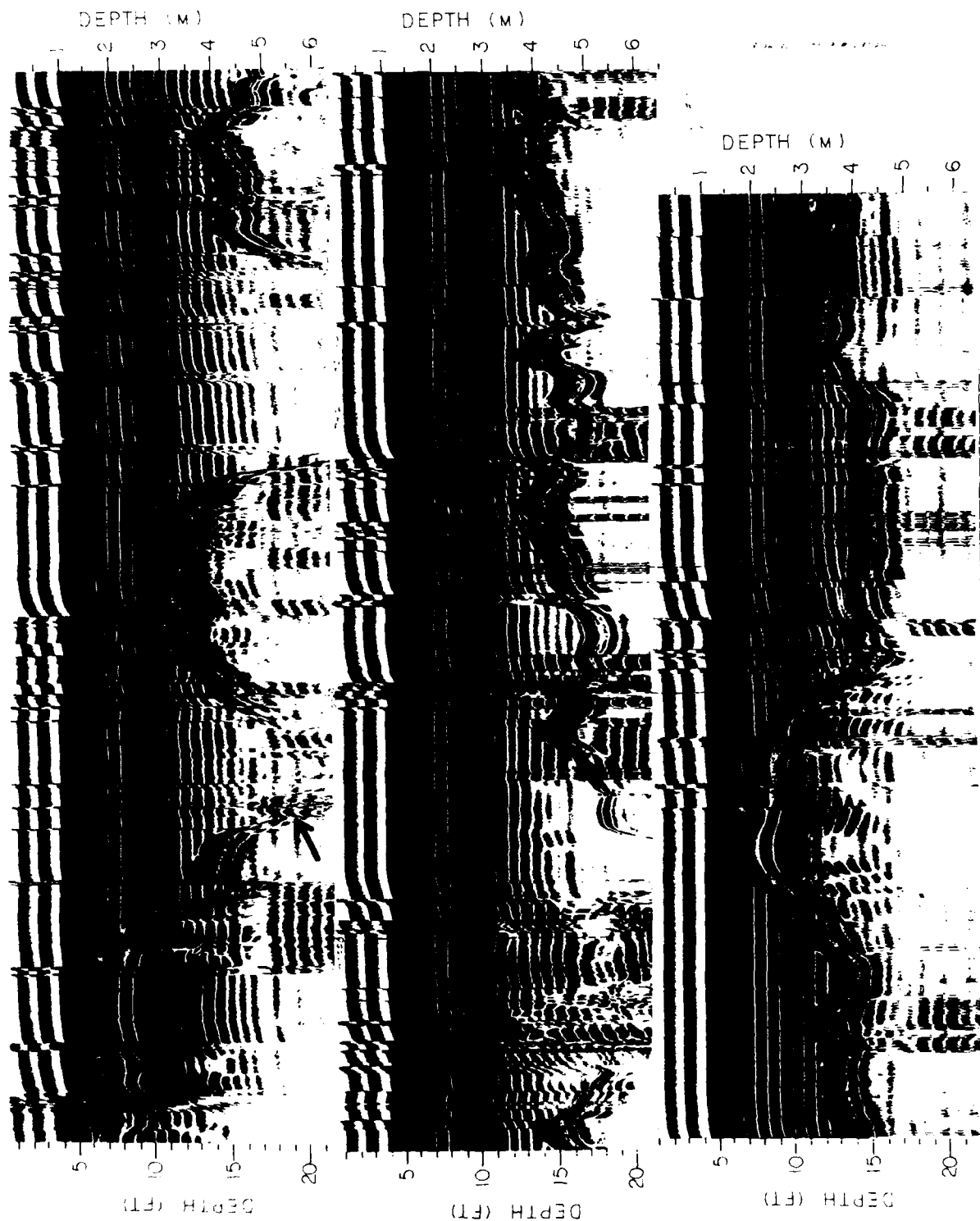
16

Figure 10. Radar profiles alongshore over revetment mat

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and, therefore, seriously interferes with all bottom information at a depth of 11 ft or less. Suggestions for minimizing these events are given in paragraphs 28 and 29. The reflection of the downward radiated signal is within this direct coupling region at the left of the upper profile. Here, this reflection and the direct coupling interfere to produce an apparently higher frequency signal, but this is not true. Below 11 ft, the bottom reflection contains the true character of the downward radiated signal. The time duration of the two dark bands (or one oscillation of the wavelet) is about 17 ns, and this translates to a center frequency of approximately 60 MHz. This is surprisingly low in view of past performance of the Model 3207 antennas on land and reflects the severe loading caused by the water environment. It is also low enough to prevent any penetration of the revetment wire grid. The vertical stack of horizontal bands labeled "loss of contact" are believed to be resonances between antenna and water surface when either of the antennas was lifted from the water surface.

22. Immediately below the bottom reflection is a return labeled "secondary event." The origin of this event is not clear, but is not believed to represent sedimentary layering beneath the revetments because of arguments presented in paragraph 21. Additionally, it parallels the bottom reflection too precisely, is too uniform to be sedimentary layering beneath the revetments, and is at too great a time delay to be a reflection from the bottom of the revetments. The author's speculation is that the return is (a) the true revetment reflection and the bottom reflection is from an overlying mud layer; or (b) a secondary emission associated with the structure of the antenna package. If it is from a mud layer, then the layer must be more than several feet thick. Therefore, some ground truth must be carried out to determine the origin of these events.

23. The bottom reflection diminishes completely at about 7 m, and this corresponds to a total propagation loss of about 86 dB. The value of 0.02-S/m conductivity is a guess for this section of the Mississippi River (no data on water conductivity or temperature were gathered at the time of the survey). The conductivities of several midwest rivers feeding the Mississippi are higher at about 0.03 S/m, and this would predict 109 db for 7-m depth at 60 MHz.

24. Of great interest in the profiles of Figure 9 are the hyperbolic shapes originating within the bottom reflections. These are indicated by the

heavier black arrows and may be too faint to be seen in the reproduction of the figure. They are associated with any sort of disturbance in the continuity of the bottom; presumably erosion or displacement in the revetment mat. The use of a positioning system would have allowed their location and investigation.

25. A second feature of interest is the wavy modulation most evident in the bottom reflection of the lower profile of Figure 9. It may have been surmised by Mr. Dean ("The ripples of the mat elements can be seen beneath the smooth mud layer," communication to Mr. Henry Thornton of WES dated March 21, 1986, found in Mr. Dean's file) that these are responses to individual concrete blocks, although it is not readily apparent why a flat mat of blocks should produce a modulation in depth. They could also be depth modulations due to surface water waves. Since no distance scale is available, these ideas are only speculation.

26. Figure 10 is a more extensive alongshore profile. Again we see the extensive interference of the direct coupling. The bottom profile is not visible in several sections, and the reason for this is not clear. The rapid increase in range (depth) at the margins of these zones indicates a rapidly deepening section. Most of these transitions are smooth and not associated with hyperbolic patterns. The depth scale shows these variations to be greater than 10 ft, and it would be important to know if this is expected for this area. Personal notes of Mr. Dean indicate that these areas were muddy, but it is difficult to see how this was concluded if the note referred to the bottom condition.

27. Figure 10 also shows the same secondary event structure beneath the bottom reflection that occurs in Figure 9. It is more difficult to follow because of the direct coupling interference, but the middle profile contains sections where the two events can be readily distinguished. As in Figure 9, the secondary event parallels the bottom reflection almost perfectly.

Conclusions and Recommendations

28. Although there are many aspects of this survey that, in retrospect, could definitely have been improved upon, there is no doubt that much useful information may be contained in these radar profiles. The most important conclusion is that the system does profile the bottom to near 25-ft depths and

does respond to local disturbances. These disturbances must be within or above the revetments because the wire grid of the revetments prevents deeper penetration given that the diagram of Figure 8 is correct. A desirable aspect of the project would have been more experimentation or ground truth (i.e. river bottom truth). The extent of mud cover on the revetments and the cause of the many interesting phenomena observed in the records, especially the double bottom returns and the hyperbolae, could have been determined by further testing. The survey itself is in great need of an accurate positioning system (or a buoy grid on the river) to locate areas of interest. Sophisticated signal processing schemes do not seem necessary.

29. Specific recommendations for improvements in survey techniques are:

a. Greater separation of antennas to suppress reverberation.

b. Greater ballast to reduce any possible lifting of the antennas above the water.

c. Reorienting the antennas with their altitudinal axes parallel, also to reduce reverberation.

d. Greater power to improve penetration. It is possible that these antennas were equipped with a specially made high voltage pulser from GSSI. However, the conformity of the range to theoretical expectations for a standard system seems to preclude this.

e. Better matching of antenna impedance in the water environment to increase transmitted power. This would be a costly design procedure, but well worth the investment if extensive surveying is planned. One small US company has built such a device, to the author's knowledge.